CHARACTERIZATION OF SECONDARY RADIATION FROM PRE-CONCEPTUAL HIGH POWER TARGETS

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To meet mission requirements, the Rare-Isotope Accelerator (RIA) is being designed to accelerate primary beams of stable ion species from hydrogen through uranium. If it is determined to be technically feasible, systems will be designed to accommodate beam powers up to 400 kW [Gr99]. Several technical issues should be addressed at the pre-conceptual design stage to guide future design efforts. First, the magnitude of the prompt radiation, attendant activation and radioactive material inventory generated at the target stations must be understood as these will be significant elements of the overall facility hazard category rating, and determine much of the bulk shielding and civil engineering design requirements. Second, the radioactive material inventory generated at and around target stations, beam dumps, strippers and catchers must be understood, as it will be a significant element (if not the primary element) of the overall hazard analysis and classification of the facility. The facility classification, in turn, will drive the scope and magnitude of ensuing design efforts. Facility classification studies are only just beginning [Ah03, Ro03]. Finally, total radiation doses and their spatial distributions from interactions in materials by both primary and secondary ion beams must be characterized. This information is critical in determining optimum material choices for magnet construction, targets, beam dumps, catchers, and slits, and to help address facility layout design, radiological requirements, and maintenance issues.

Tools, data, and extensive experience gained from the design of the 2 MW Spallation Neutron Source (SNS) accelerator facility currently under construction at the Oak Ridge National Laboratory will be directly applicable to characterizing the radiation from light-ion beams interacting with proposed pre-conceptual high power target designs for RIA. Of particular relevance to this proposal is the development of the Activation Analysis Sequence (AAS) [Od98b, McN00] and extension of the ORIHET code [Cl88]. These code systems were developed to interface with the MCNPX code [Hu99] being developed at Los Alamos National Laboratory (LANL) in support of the Accelerator Production of Tritium (APT) project. They provided detailed radioactive isotopic inventories of SNS components and structures for the determination of hazard category classification, remote handling requirements, shielding design, and decommissioning and decontamination requirements. Publications and reports representative of the utilization of these tools for the SNS project, by Harrington *et al.* [Ha98], Johnson *et al.* [Jo00a and Jo00b], Ludwig [Lu99], Miller *et al.* [Mi00], Odano *et al.* [Od98a], Popova *et al.* [Po00], Remec [Re00], and Yugo [Yu00], are included in the Cited Literature section. In addition, we will use newly available computational tools, *e.g.* PHITS, for characterizing radiation from heavy ion interactions [Iw00, Iw01, Iw03]. Both the light ion transport and heavy ion transport codes utilize the same geometry modeling techniques. Consequently, extending the AAS interface to include the heavy ion transport code is straightforward.

Benchmark calculations will need to be performed to compare to existing data for quality assurance. The ion beam species and specific energies currently planned for RIA include 930 MeV protons up to 400 MeV/u uranium, with specific energies of intermediate-mass heavy ions reaching about 500 MeV/u. Protons having energies of 930 MeV and ^{3}He ions having specific energies of 612 MeV/u will be the most penetrating and intense. For protons, data exist from many proton accelerators in this energy range. Semi-empirical methods and Monte Carlo have been successfully employed for preliminary safety analysis and design, and these can be benchmarked against relatively abundant data. Light ion Monte Carlo transport calculations are possible for beams of protons, deuterons, ^{3}He, and ^{4}He ions. In addition to the light ions, there will be considerable time devoted at RIA to the use of primary heavy ion beams and fast-fragment techniques. Heavy ion beams produce low-Z and high-Z fragments that must be characterized and transported, for they also produce radiation dose by further interactions. However, for transport of ions heavier than ^{4}He, Monte Carlo transport calculations are still under development and benchmarking is just beginning. Beta versions of promising codes have just recently been made available [Iw00, Iw01, Iw03]. Data on secondary radiation from heavy ion interactions are still relatively sparse, but necessary to benchmark calculations. There exist only several experimental studies of neutron spectra from heavy-ion thick-target interactions. These include: data from ^{4}He -induced reactions by Heilbronn *et al.* [He99], Kurosawa *et al.* [Ku99a], and Kato and Nakamura [Ka92] (the results by Kato and Nakamura include analysis by Monte Carlo calculations); data from ^{12}C-induced reactions by Heilbronn *et al.* [He99], and Kurosawa *et al.* [Ku99a]; data from ^{20}Ne-induced reactions are available from Kurosawa *et al.* [Ku99b] and McCaslin *et al.* [McC85]; data for ^{93}Nb-induced reactions are available from Heilbronn *et al.* [He98]; data for neutron yields from thick C, Al, Cu, and Pb targets bombarded by 400 MeV/nucleon Ar, Fe, Xe, and 800 MeV/nucleon Si ions are available from T. Kurosawa *et al.* In addition, neutron production cross-section data are now becoming available [Iwa01]. It is very important to understand and to be able to model reactions and production of secondary radiation from heavy ion beams. The radiation patterns differ significantly from proton-induced reactions. For example, the multiplicity of neutrons in a heavy ion reaction is larger than for a proton-induced reaction at a given specific energy. For the same power, one might expect protons to produce the largest number of neutrons because the ion range and beam particle current is largest for protons. However, preliminary Monte Carlo calculations indicated that, for the same power, the 612 MeV/u ^{3}He ion beam produced more neutrons than a proton beam having800 MeV. Compounding this, heavy ion neutron production angular distributions are much more highly peaked in the forward direction compared to those from protons. These features are illustrated in Figure 1. Issues of yield and angular distributions of secondary radiations must be studied further by way of simulation or measurement, to help focus bulk shielding, target and target area R&D, and magnet R&D.

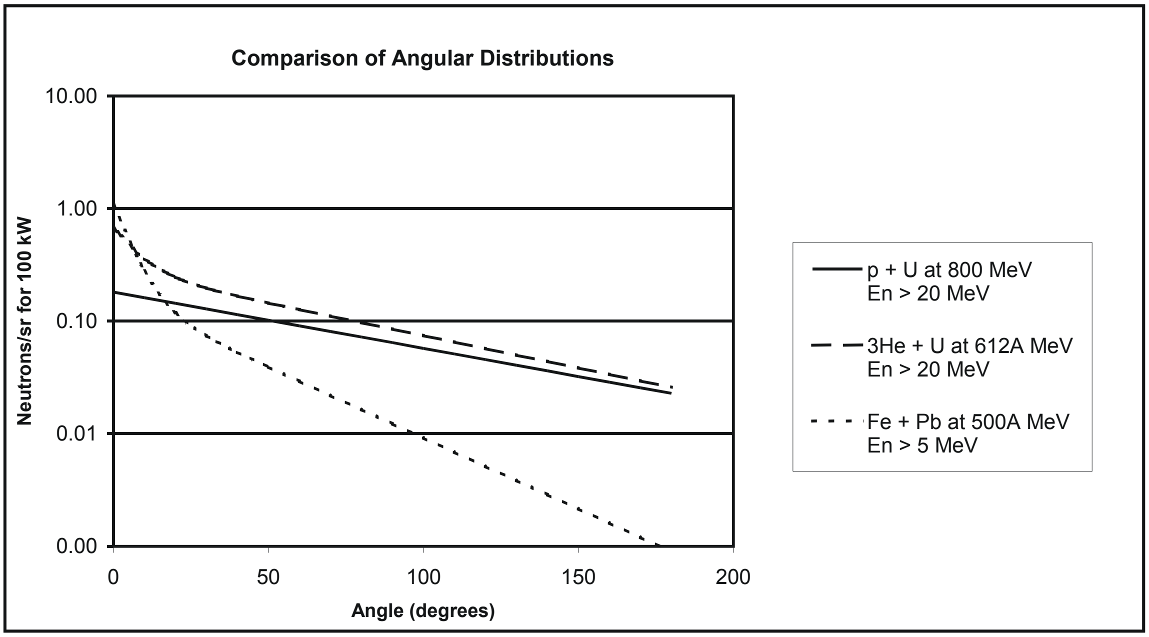

Figure 1 Angular distributions of neutrons from proton and ^{3}He-ion beams on a stopping uranium target, and from an iron ion beam on a stopping lead target are shown for the same beam power. The proton and ^{3}He results are from Monte Carlo calculations, and the Fe + Pb results are generated from experimental data at 400A MeV [Ku01], scaled to 500A MeV using $(E/A)^2$-scaling [Ku01].

The RIA complex will have up to three stations housing production targets for ISOL (Isotope Separation On-Line) studies. The production targets will consist of various elements or compounds chosen to optimize production of the rare isotope ion species of interest. Several designs exist based on those used at CERN (ISOLDE), TRIUMF, and Rutherford Lab. These targets will be most useful when employed with high-intensity light ion beams, such as protons, deuterons and ^{3}He. The RIA complex will also have two fast-beam target systems: one supports the high-energy (HE) facility, where fragments are transported for in-flight experiments, and one will also support the low-energy (LE) facility, where the fragments stop in a gas cell and then are transported to a low energy facility. Each fast beam target system consists of a production target module (one target currently being considered is liquid lithium), a fragmentation separation device, fragment beam "catcher bars" for stopping unwanted fragments, a beam dump for non-interacting primary beam, local shielding, and bulk shielding. Unlike the ISOL target systems, these components are distributed, and some components such as Fragment Separator (FS) magnets will be in close proximity to loss regions and experience significant radiation doses. The production target of the Fragment Separator (FS) is a source of large fluxes of high-energy neutrons, photons, low-Z charged particles and many secondary high-Z fragments. For a 400 kW beam, up to 100 kW will be deposited in the target. Copious numbers of secondary fragments will be produced that have magnetic rigidities both lower and higher than the primary beam. Since the fragments are spatially diffuse, catcher bars as beam stops are being considered. However, a full characterization of radiation fields from primary beam dumps and secondary catchers is necessary to guide design efforts of these devices. The problems that can be addressed by our calculations are removal of the heat, constructing the bars and associated hardware of materials that are resistant to the radiation fields and constructing them to accommodate remote handling if they, or the magnet, need replacing. A bigger problem is associated with removing the primary beam. Since the desired fragments may have either lower or higher magnetic rigidity than the primary beam, the primary beam will need to be removed in different locations in the magnet. This is logically accomplished by having a non-fixed beam line that takes the beam out of the dipole. Here also will be moving parts that may need repair or servicing. It is critical to understand the residual radiation fields to design for these difficult issues. In order to understand the magnitude of the problems, some fundamental questions need to be answered. These include the total dose and the spatial distribution of the dose relative to the components of the RIA facility. One would like to construct radiation resistant components such as magnets. However, in order to choose the appropriate technology and materials, the dose needs to be calculated prior to the choice. It is critically important to the cost of magnet design and construction to understand these issues as early as possible in the design stage.

It is planned to address prompt radiation, activation, radiation heating and material damage issues using the MCNPX code [Hu99], and the PHITS code [Iw00, Iw01, Iw03], coupled to the Activation Analysis Sequence (AAS) [Od98b, McN00] and extension of the ORIHET code [Cl88]. The PHITS code should provide us with a presently unique computational tool for transporting heavy ions.

In conclusion, support for radiation characterization is vital to RIA R&D. The magnitude of the prompt radiation, attendant activation, heat production, radiation damage and radioactive material inventory generated must be understood. These will be significant elements of the overall facility hazard category rating, bulk shielding, engineering requirements on design and optimum material choices for magnet construction, targets, beam dumps, catchers, and slits, and to help address overall facility layout design, radiological requirements, and maintenance issues materials. It is important that yields and angular distributions of secondary radiation from heavy ion reactions must be understood and radiation environments simulated. New codes will be employed simulations. However, benchmarking will be necessary, and to do this the proper data sets must be available or else obtained.

Literature Cited

[Ah03] "*Scoping Inventory Calculations for the Rare Isotope Accelerator*," L.E. Ahle and J.L Boles, LLNL Report UCRL-ID-154783 (2003).

[Br86] "*MCNP - A General Purpose Monte Carlo Code for Neutron and Photon Transport*," J.F. Briesmeister, Ed., LANL Report LA-7396-M, Rev. 2 (1986).

[Cl88] "*HERMES, A Monte Carlo Program Systems for Beam Material Interaction Studies*",P. Cloth, et. al., KFA Jülich, Report Jul-2203 (1988).

[Gr99] *"ISOL Task Force Report to NSAC"*, H. Grunder (chair), November 22, 1999 (unpublished).

[Ha98] "*Initial Investigations of SNS Target Facility Accident Source Terms"*, R. M. Harrington, J. R. Devore, E. C. Beahm, C. F. Weber, and J. O. Johnson, Proceedings for the 2nd International Topical Meeting on Accelerator Applications of Accelerator Technology, Gatlinburg, Tennessee, September 20-23, 1998.

[He98] "*Neutron Yields from 435 MeV/nucleon Nb Stopping in Nb and 272 MeV/nucleon NbStopping in Nb and Al"*, L.Heilbronn, R.Madey, M.Elaasar, M.Htun, K.Frankel, W.G.Gong, B.D.Anderson, A.R.Baldwin, J.Jiang, D.Keane, M.A.McMahan, W.H.Rathbun, A.Scott, Y.Shao, J.W.Watson, G.D.Westfall, S.Yennello, and W.-M.Zhang, Phys. Rev. C **58**, 3451 (1998).

[He99] "*Neutron Yields from 155 MeV/Nucleon Carbon ad Helium Stopping in Aluminum"*, L.Heilbronn, R.S. Cary, M. Cronqvist, F. Deák, K. Frankel, A. Galonsky, K. Holabird, Á.Horvath, Á. Kiss, J. Kruse, R.M. Ronningen, H. Schelin, Z. Seres, C.E. Stronach, J.Wang, P. Zecher, and C. Zeitlin, Nucl. Sci. and Engin. **132**, 1 (1999).

[Hu99] "*MCNPX for Neutron-Proton Transport*", H. G. Hughes et al, International Conferenceon Mathematics & Computation, Reactor Physics & Environmental Analysis in NuclearApplications, American Nuclear Society, Madrid, Spain, September 27-30, 1999.

[Iw00] "*Development of heavy ion transport Monte Carlo code*", Hiroshi Iwase, Tadahiro Kurosawa, Takashi Nakamura, Nobuaki Yoshizawa, and Jun Funabiki, SATIF-5, Paris, France, 18-21 July 2000.

[Iw01] "*Development of heavy ion transport Monte Carlo code*", Hiroshi Iwase, Tadahiro Kurosawa, Takashi Nakamura, Nobuaki Yoshizawa, and Jun Funabiki, Nucl. Inst. Meth. Phys. Res. **B183**, 374(2001).

[Iw03] Hiroshi Iwase, Ph.D. thesis, Tohoku University, unpublished.

[Iwa01] *"Double-Differential Cross Sections for the Neutron Production from Heavy-Ion Reactions at Energies E/A = 290-600 MeV",* Y. Iwata, T. Murakami, H. Sato, H. Iwase,

T. Nakamura, T. Kurosawa, L. Heilbronn, R.M. Ronningen, K. Ieki, Y. Tozawa, and K. Niita, Phys. Rev. C **64**, 054609(2001).

[Jo00a] "*The Spallation Neutron Source (SNS) Proton Beam Transport System Activation Analyses To Support the Environmental Impact Statement*", J. O. Johnson, G. S. McNeilly, and J. M Barnes, Oak Ridge National Laboratory, SNS-106100200- R0008-R00, (2000).

[Jo00b] "*The Application of the Activation Analysis Calculational Methodology to the Spallation Neutron Source (SNS) Target Station Monolith Conceptual and Preliminary Title I design*", Jeffrey O. Johnson, Naoteru Odano, and John M. Barnes, Oak Ridge National Laboratory, SNS-106100200-TR0040-R00, (2000).

[Ka92] *"Estimation of neutron yields from thick targets y high energy 4He ions for the design for a heavy ion medical accelerator",* T. Kato and T. Nakamura, Nucl. Instr. Meth. Phys. Res. **A311**, 548 (1992).

[Ku99a] "*Measurements of Secondary Neutrons Produced from Thick Targets Bombarded by High-Energy Helium and Carbon Ions"*, T. Kuroswawa, N. Nakao, T. Nakamura, Y.Uwamino, T. Shibata, N. Nakanishi, A. Fukumura, and K. Murakami, Nucl. Sci. and Engin. **132**, 30 (1999).

[Ku99b] *"Measurements of Secondary Neutrons Produced from Thick Targets Bombarded by High-Energy Neon Ions",* Tadahiro Kuroswawa, Noriaki. Nakao, Takashi Nakamura,Yoshitomo Uwamino, Tokushi Shibata, Akifumi Fukumura, and Ken Murakami, J.Nucl. Sci. and Tech. **36**, 41 (1999).

[Ku00] *"Neutron Yields from Thick C, Al, Cu, and Pb Targets Bombarded by 400 MeV/nucleon Ar, Fe, Xe, and 800 MeV/nucleon Si Ions",* T. Kuroswawa, N. Nakao, T. Nakamura, H. Iwase, H. Sato, Y. Uwamino, and A. Fukumura, Phys. Rev. C **62**, 044615 (2000).

[Lu99] "*Preliminary Estimate of Dose Following Machine Shutdown From Collimators, Vacuum Chamber Walls, and Adjacent Magnets*", Hans Ludwig, Oak Ridge National Laboratory, SNS-106100200-TR0003-R00, (1999).

[Ma83] *"Total Inclusive Neutron Cross Sections and Multiplicities in Nucleus-Nucleus Collisions at Intermediate Energies"*, R.Madey, B.D.Anderson, R.A.Cecil, P.C.Tandy, and W.Schimmerling, Phys.Rev. C **28**, 706(1983).

[McC85] *"Neutron production by Ne and Si ions on a thick Cu target at 670 MeV/A with application to radiation protection"*, J.B. McCaslin, P.R. LaPlant, A.R. Smith, W.P. Swanson, and R.H. Thomas, IEEE Trans. on Nucl. Sci. **NS32**, No.5, 3104(1985).

[McN00] "*The Activation Analysis System (AAS)*", Greg S. McNeilly, Oak Ridge National Laboratory, SNS-101040200-TR0003-R00, (2000).

[Mi00] "*Radiation Transport Analysis in Support of the SNS Target Station Neutron Beamline Shutters Title I Design*", T. M. Miller, R. E. Pevey, R. A. Lillie, and J. O. Johnson, Oak Ridge National Laboratory, SNS-106100200-TR0049-R00, (2000).

[Od98a] "*Shielding and Activation Analyses in Support of The Spallation Neutron Source (SNS)ES&H Requirements"*, Naoteru Odano, Jeffrey O. Johnson, R. Mike Harrington, andJoe R. Devore, Proceedings for the 1998 American Nuclear Society Radiation Protection and Shielding Division Topical Conference on Technologies for the New Century, Nashville, Tennessee, April 19-23, 1998, Vol. I.

[Od98b] "*Development of the Activation Analyses Calculational Methodology for the Spallation Neutron Source (SNS)"*, Naoteru Odano, Jeffrey O. Johnson, Lowell A. Charlton, and Johnnie M. Barnes, Proceedings for the 1998 American Nuclear Society Radiation Protection and Shielding Division Topical Conference on Technologies for the New Century, Nashville, Tennessee, April 19-23, 1998, Vol. II.

[Po00] "*Shielding and Activation Analyses for the SNS 200 kW Ring Injection Dump Title I Design*", I. Popova amd J. A. Bucholz, Oak Ridge National Laboratory, SNS-106100200-TR0026-R00, (2000).

[Re00] "*Analysis of the Mercury Activation from the Mercury Target Tests at the LANSCE WNR Facility*", I. Remec and D. C. Glasgow, Oak Ridge National Laboratory, SNS-101040300-TR0003-R00, (2000).

[Ro03] "*Preliminary Study of Radiation Issues at the Rare Isotope Accelerator"*, R.M. Ronningen, A.F. Zeller, L.H. Heilbronn, Y. Iwata, K. Murakami, H. Iwasi, and T. Nakamura, Accelerator Applications in a Nuclear Renaissance, Accelerator Applications Meeting, American Nuclear Society, San Diego, CA, June 1-3, 2003.

[Yu00] "*Preliminary Shielding and Activation Analyses of the Spallation Neutron Source Proposed T0 Chopper Design*", James J. Yugo, Oak Ridge National Laboratory, SNS-107030700-TR0005-R00, (2000).